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RADIATION FROM INTENSE ELECTRON BEAMS
ASSOCIATED WITH
THE CERENKOV MECHANISM

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John R. Neighbours and Fred R. Buskirk

Abstract

This report summarizes the Cerenkov radiation to be expected from an intense electron beam for both the coherent and incoherent modes of radiation. The effects of a finite length beam are discussed with regard to beam diffraction, radiated power, and bunch shape. The appendices contain a discussion of the beam radiation pattern.

RADIATION FROM INTENSE ELECTRON BEAMS ASSOCIATED WITH THE CERENKOV MECHANISM

1. INTRODUCTION

Normally a charge or system of charges moving at constant velocity does not radiate electromagnetic energy, but if the velocity of the charge is greater than the velocity of light in a medium, radiation occurs. It is broad band; the intensity increases with frequency; and the propagation is confined to a cone, much like a shock wave in air. Equations (2) and(3) in a later section describe these results. In previous work [1-4], we described theory and experiments showing that this mechanism produces microwaves from bunched electron beams, in addition to the usual optical radiation, as studied by Cerenkov and many others.

In this report we consider aspects of coherent Cerenkov radiation, with emphasis on radio and microwave frequencies. As will be shown, power levels may become very high, in the megawatt range, so that serious consideration should be given to this mechanism. The scope of this report is to outline the systematics of a theory in which the dielectric (which lowers the velocity of light) is considered to be linear and non-dispersive. The aspects considered which are not treated in the extensive literature are calculations for electrons occurring in finite size bunches, both single and repeated. Future work should aim at the effect of ionization in the dielectric medium, betatron oscillations of the beam electrons, and other mechanisms which could seriously modify or degrade the radiation.

2. SUMMARY OF PREVIOUS WORK

In the earlier work[1-4], it was assumed that electrons were emitted from an accelerator in bunches, described by a charge density $\rho(\vec{r})$, and all had the same velocity $\vec{v}$ such that the bunch did not change shape in time. The current density is then given by

$$\vec{J}(\vec{r}) = \rho\,\vec{v} \tag{1}$$

A. Intensity

Under these conditions, the Cerenkov radiation in a medium with the velocity of radiation $c < v$ is

$$\frac{dE}{dx} = \frac{\mu}{4\pi}\,\omega d\omega\,\sin^2\Theta_c\,q^2\,F^2(\vec{k}) \tag{2}$$

$$\frac{dE}{dx} = \frac{\mu}{4\pi}\,\omega\omega_0\,\sin^2\Theta_c\,q^2\,F^2(\vec{k}) \tag{3}$$

Eq. (2) refers to a single bunch, the radiation has a continuous frequency spectrum, and the formula gives the energy radiated at angular frequency ω in a range $d\omega$, per unit length. Eq. (3) is the energy-per-unit path per bunch for the case of periodic bunches, emitted at an angular frequency ω_o. Here ω is a harmonic of ω_o, in contrast to the continuous frequency spectrum of Eq. (2). In both cases, q is the total charge of one bunch, and $F(\vec{k})$ is a form factor for the charge distribution

$$F(\vec{k}) = q^{-1}\iiint \rho(\vec{r})\,e^{i\vec{k}\cdot\vec{r}}\,dV \tag{4}$$

Θ_c is the Cerenkov angle,

q is the charge per bunch, and $\vec{k}$ is propagation vector for the emitted radiation, such that $k = \omega/c$, and the direction is along the Cerenkov cone.

B. Polarization

The electron field is in the plane of the observer and the electron path, as it is for usual optical Cerenkov radiation.

C. Coherence

If the charge is a point charge, $F = 1$ and in fact, for a finite bunch, we will have $F \sim 1$ for $k\ell << 1$, where $k = 2\pi/\lambda$. This corresponds to $\lambda > \ell$, where ℓ is the size parameter of the bunch. For these long wave lengths, either formula, Eq. (2) or (3), shows that the intensity is found by setting $q = ne$ where n is the number of electrons in the bunch. Thus the intensity is proportional to n^2e^2. As higher frequencies are examined, the factor F becomes small, and finally, for very high frequencies (optical range), we would expect incoherent radiation, in which q^2 is replaced by ne^2.

D. Diffraction Effect

An important result is that if the region of emission of radiation is finite, of length L, the emitted radiation is no longer confined to the Cerenkov cone $\Theta = \Theta_C$ but is spread about that angle and the spreading depends on the length of the path in the gas and the wave length of the radiation. It is more closely related to the diffraction pattern of an end fire antenna, rather than the broadside array; the latter is related to the single slit of optics. This effect is independent of bunch size and repetition rate. Associated with diffraction is an enhancement, qualitatively described below.

E. Enhancement from Diffraction

In most diffraction or interference situations in optics, the energy is usually redistributed in angle if parameters are changed. For example, if the width of a single slit is changed but the total power passing through the slit remains constant, the total power integrated over the diffraction pattern on a screen remains constant. In the Cerenkov case, the development of Ref. 3 showed that for small Cerenkov angles, the intensity at θ_c remains constant as L decreases, but the total power radiated at angles $\theta > \theta_c$ increases dramatically. The total power radiated increases by factors of up to 50 in our experimental situation.

F. Form Factor Effect

The basic Cerenkov radiation strength tends to increase with frequency, for either coherent or incoherent emission. Starting at low frequencies, the coherent emission increases with ω until F becomes small, at $\omega = \omega_m$. At this frequency, the wave length is short enough so that radiation emitted from electrons at the front and rear of the bunch begin to interfere destructively. This leads to destructive interference and lowered emissions of power above ω_m. Experiments in principle could demonstrate this effect, but at this time we have been unable to make measurements in the high frequency microwave range ($\lambda \sim 2$ mm) which would quantitatively demonstrate the predictions.

As a further remark, it should be possible with precise measurements to determine size parameters of the electron bunches at a distance, or, in other words, to do beam diagnostics by this method. These possibilities will be explored in another report.

3. Approximate Results for Radiated Power

The results mentioned previously may be related to more conventional parameters of pulse length and peak current. If we assume a pulse in the form of a uniform cylinder, $J = \rho v$ and the current $I = JA$, $q = \rho A\ell = \rho AvT$ where ℓ = the length of the bunch and T = the bunch length measured as a time. Thus we find

$$q = IT \tag{6}$$

For a Gaussian pulse, the charge density is

$$\rho = \rho_0 \, e^{-(x^2 + y^2)/a^2} e^{-b^2 z^2/b^2} \tag{7}$$

It may be shown that the peak current in the middle of the pulse (at $z = 0$) is

$$I_o = \frac{v}{\pi b} q \tag{8}$$

and that the normalization constant ρ_o is related to the total charge of the bunch by

$$q = \rho_o \pi^{3/2} a^2 b \tag{9}$$

Then we may let the effective length of the bunch be $\ell = b\pi$ and use $q = I_0 T = I_0 \ell/v$, just as for the uniform cylinder.

Now consider the sum over frequencies in Eq. (3). Assuming that $F(k)$ is constant up to some k_{max} which corresponds to $\omega_m = N\omega_0$, we find

$$\sum \omega\omega_0 = \sum n\,\omega_0{}^2$$
$$= N(N+1)\ \omega_0{}^2/2$$
$$\simeq N^2\omega_0{}^2/2$$
$$= \omega_m{}^2/2$$

Thus

$$\sum \omega\omega_0 = \omega_m{}^2/2 \tag{10}$$

For a single bunch, the sum over the continuous frequency distribution (2) gives

$$\int_0^{\omega_m} \omega d\omega = \omega_m{}^2/2 \tag{11}$$

Thus the results of Eqs. (10) and (11) above may be used for either single or repeated pulses to calculate the total power radiated at all frequencies.

Now we may use the results of Eq. (6)-(9) to re-express the results of Eq. (2) or (3). The latter may be multiplied by v to convert to power, then summed or integrated over ω for the total power emitted, which is

$$P = \frac{\pi r_0}{2}\ v\ \sin^2\theta_c\ I_0^2\ T^2\ f_m^2 \tag{12}$$

This holds for either periodic or a single bunch. In either case it is the rate at which electromagnetic radiant energy is emitted while the bunch is in flight, per bunch (in the case of periodic bunches).

Noting that $f_m = 1/T$ holds, which is equivalent to the uncertainty relation in quantum theory or the bandwidth-pulse length relation in communications,

$$P = \frac{\pi \mu_0}{2} v \sin^2\Theta_c \; I_0^2 \qquad (13)$$

Thus the power emitted for coherent radiation is proportional to the square of the beam current. This makes explicit one of the main points of this report: that the emitted power increases rapidly with the beam current. Thus, although weak beams emit little radiation, the radiation becomes important for large currents. When we note that the radiation emitted is proportional to I_0^2 but the energy in the beam is proportional to I_0, so that relative efficiency as a radiator increases in proportion to I_0. This may be made quantitative by multiplying (13) by L/v to get the total energy emitted by the bunch during its flight through a path L, where L is the range. The energy put into the bunch is I_0T, so that the efficiency ε, defined as the ratio of the energy radiated (Cerenkov) to the total energy of the beam becomes

$$\varepsilon = \frac{r_0 \pi}{2} \sin^2\Theta_c \frac{I_0}{T} \frac{L}{V_0} \qquad (14)$$

where V_0 is the energy of the beam expressed in volts and L is the range of the beam in air. Strictly speaking, L is the distance at which Cerenkov radiation ceases. The precise value of L would depend on the relative importance of bremsstrahlung, ionization, and instabilities which could disperse the electron bunch, and these aspects should be considered in greater detail.

The overall systematics of the radiation associated with the Cerenkov mechanism are expressed by Eq. (12), (13), and (14). The following features should be noted:

A. The power radiated per bunch (eq. 12, 13) is proportional to the square of the peak beam current, I_0^2, and is independent of the pulse length T. This depends on the approximation that $f_m T = 1$, where T is the pulse length and f_m is the maximum frequency for which the fourier transform of the pulse has significant strength. This expression for the power radiated is the energy-per-unit time while the bunch is in flight, from the accelerator to the point where it ceases to radiate effectively. The latter point in the simplest consideration is the point at which the bunch has lost enough energy so that it is below the threshold for Cerenkov radiation, which is 20 MeV for electrons in normal air.

B. As T is decreased, assuming I_0 is constant, the power radiated remains constant. But the frequency at which most of the radiation occurs is increased as T is decreased.

C. The efficiency (Eq. 14) depends on I_o/T showing that for high currents and short bunches, the Cerenkov mechanism could not only lead to sizable amounts of radiation but also dominate the other modes of energy loss.

D. As a guide to what may be expected in the case of plasma shielding, we might expect that some length ℓ' of the nose of the beam bunch might be unshielded by the plasma. From the above considerations, the length ℓ' would not change the total power radiated, but would change dramatically the frequency at which the radiation occurs. This is because if only the nose region of of length ℓ' radiated, the total effective radiating charge would be proportional to ℓ'. But the frequency of the maximum radiation would increase as $1/\ell'$, so the power radiated would remain constant as ℓ' is varied.

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APPENDIX A - EXTREME VALUES OF THE RADIATION FUNCTION

The radiated power per unit solid angle $W(\nu,\vec{n})$ can be written as the product of two factors:

$$W = Q\ R^2 \tag{A1}$$

where Q is a function having the dimensions of power (watts) and R is a dimensionless radiation function.

$$Q = \frac{\mu c\ \nu_0^{\ 2}}{8\pi^2}\ q^2 \tag{A2}$$

$$R = (kL)\ \mathrm{Sin}\Theta\ F(\vec{k})\ I(u) \tag{A3}$$

Here, μ is the permeability of the medium, c is the velocity of light in the medium, and q is the charge of an individual electron bunch. If an RF Linac is the source of the electrons, the frequency ν_o is that of the Linac; however, in all cases, ν_o corresponds to the spatial periodicity, $\ell = c/\nu_o$, of the electron bunches.

In (3), k is the wave vector of the emitted radiation, L is the beam interaction length, and $F(\vec{k})$ is the form factor defined such that

$$\rho_0'(\vec{k}) = q\ F(\vec{k}) \tag{A4}$$

and $\rho_0'(\vec{k})$ is the Fourier transform of the charge distribution of an individual charge bunch. The diffraction function

$$I = \frac{\mathrm{Sin}\ u}{u} \tag{A5}$$

is a function of the diffraction variable

$$u = \frac{kL}{2}\ (\mathrm{Cos}\Theta_c - \mathrm{Cos}\Theta) \tag{A6}$$

and consequently, R is a somewhat complicated function of Θ and kL.

MINIMUM VALUES

By inspection, it is obvious that R^2 and thus W will have minima when , $I(u) = 0$. These true zeroes of the function occur when u is equal to integral values of π; i.e., $u = m\pi$. Substituting this condition in (A6) leads to the angular values for the zeroes in the radiated power

$$\cos\Theta = \cos\Theta_c - m\frac{2\pi}{kL} \qquad \text{(A7)}$$

which can be written in terms of the wavelength (in the medium) of the radiation as

$$\cos\Theta = \cos\Theta_c - m\left(\frac{\lambda}{L}\right) \qquad \text{(A8)}$$

This relation is exact and gives the zeroes of R for all allowed values of m for which $\cos\Theta \leq 1$. $I(u)$ is a maximum at $m = 0$ (which gives $u = 0$), and the maximum in R tends to occur somewhere in that vicinity. The first zero is that one which is adjacent to the maximum and is given by (A8) when $m = +1$. Values of this angle as a function of $\frac{L}{\lambda}$ are shown as a Log-Log plot in Fig. 1. The relationship between Θ and $\frac{L}{\lambda}$ is approximately that of the inverse square root over the range $10 \leq L/\lambda < 100$. Within this range, the angular value (in degrees) of the first minimum is given by the empirical relation

$$\Theta_1 = \frac{82}{\sqrt{L/\lambda}} \qquad \text{(A9)}$$

The physical range of Θ is from 0 to π. Substitution of the successively larger positive values of $m = 2, 3, 4\ldots$ into (A7) or (A8) gives a set of increasing angles for the functional zeroes. If $\lambda/L \ll 1$, many zeroes will occur before the physical limit is reached.

In addition, if $\lambda/L \ll 1$, there is the possibility of having functional zeroes at angular values less than that of the main peak. These occur with the substitution of successive negative m values into (A7) or (A8), giving rise to subsidiary radiation maxima between the beam line and the main diffraction peak.

MAXIMUM VALUES

To find the maximum values of $W_{(\Theta)}$ one proceeds in the usual fashion by taking the derivative and setting it to zero.

$$\frac{\partial W}{\partial \Theta} = 2\, Q\, R \frac{\partial R}{\partial \Theta} = 0 \tag{A10}$$

This equation is satisfied for either $R = 0$ or $\frac{\partial R}{\partial \Theta} = 0$. The first condition is that considered above for the zeroes of the function. The remaining one, $\frac{\partial R}{\partial \Theta} = 0$, pertains to the maxima. Thus, it is sufficient to consider maximum values of R which will also be maximum values for $W \sim R^2$.

From (A3), the derivative of R is

$$\frac{\partial R}{\partial \Theta} = kL \left\{ \sin\Theta \left[F \frac{\partial I}{\partial \Theta} + I \frac{\partial F}{\partial \Theta}\right] + FI \operatorname{Cos}\Theta \right\} = 0 \tag{A11}$$

and the derivative of the diffraction function I(u) can be written

$$\frac{\partial I}{\partial \Theta} = \frac{dI}{du} \frac{\partial u}{\partial \Theta} = I' \frac{kL}{2} \operatorname{Sin}\Theta \tag{A12}$$

Substituting this value in (A11) and discounting the solution for $kL = 0$ gives the condition for maxima

$$\left\{ \operatorname{Sin}\Theta \left[I' F \frac{kL}{2} \operatorname{Sin}\Theta + I \frac{\partial F}{\partial \Theta}\right] + FI \operatorname{Cos}\Theta\right\} = 0 \tag{A13}$$

In order to proceed further, the functional dependence of the form factor F must be known.

A gausian form factor has been assumed in this and other reports.

$$F(k) = \mathrm{Exp}\ (-\alpha^2 \cos^2\Theta) \tag{A14}$$

where $\alpha = kb/4$ corresponding to a one-dimensional charge distribution

$$\rho_0'\ (\vec{r}) = q\ \mathrm{Exp}\ (-\frac{z^2}{b^2}) \tag{A15}$$

The derivative of this form factor is

$$\frac{\partial F}{\partial \Theta} = \alpha^2 \sin 2\Theta\ F \tag{A16}$$

which is small for the parameters of interest in Linac experiments; i.e., $b = 0.24$ cm, microwave frequencies, and angles up to approximately 25°. Therefore, a first approximation to solving (A13) can be obtained by setting the derivative of the form factor in (A13) to zero. The resulting approximate maxima condition is independent of F and can be rearranged so that I and its derivative are on the same side.

$$-\frac{I'(u)}{I(u)} = \frac{2}{kL} \frac{\cos\Theta}{\sin^2\Theta} \tag{A17}$$

The ratio of I' to I can be expanded as a power series in u as

$$\frac{I'}{I} = -\frac{u}{3} - \frac{u^3}{45} + \dots \tag{A18}$$

which converges rapidly for small values of u. Substituting the first term in the expansion into (A17) and subsequently eliminating the diffraction variable through its definition (A6) leads to an approximate equation for the maxima, which is cubic in $\gamma = \cos\Theta$.

$$-\gamma^3 - \cos\Theta_c\ \gamma^2 - \left[1 + \frac{12}{x^2}\right] \gamma + \cos\Theta_C = 0 \tag{A19}$$

In this equation, the beam parameters enter through the charge velocity in $\cos\Theta_c = c/v$ and the radiation wavelengths in $x = kL = 2\pi L/\lambda$. Numerical solutions can be carried out on a hand calculator with results within approximately 0.3° of those obtained from large-scale computer calculations.

Results for the major radiation lobe (the first maximum) are also plotted in Fig. 1. These also show a straight line dependence on a Log-Log plot and therefore can also be represented as a power law

$$\Theta_m = 52 \frac{1}{\sqrt{L/\lambda}}$$

which is accurate to approximately 5%.

APPENDIX B - EFFECT OF BEAM LENGTH ON THE RADIATION FUNCTION

In previous reports, several calculated curves of a radiation function $D_{(\Theta)}$ which differs only by constants from R^2 were presented. Fig. 2 is reproduced from Fig. 5 of Reference 4 and relabeled to be consistent with the notation of Appendix A. Fig. 2 shows the vartiation of the radiation function for 8.55 GHz radiation from the NPS Linac for beam interaction lengths in the vicinity of 100 cm. As noted previously in this and other reprots, increasing L tends to move the main diffraction lobe toward the beam line, and Appendix A gives an approximate formula for calculating the position of the first lobe. Fig. 3 (to different scales) shows this effect for larger beam paths from an S-Band Linac. As L increases, the principle lobe moves in toward the Cerenkov angle Θ_c; i.e., $\Theta_m \rightarrow \Theta_c$, and the radiated power per unit solid angle at the maximum increases greatly.

FIGURE CAPTIONS

Fig. 1 Cerenkov radiation extremum angles in degrees vs L/λ. The wavelength λ of the Cerenkov radiation is measured in the medium in which the path length is L. Curve B is for the first minimum, the solution to (A8) with $m = +1$. Curve A is for the first maximum, the solution to the approximate equation (A19). Over the range shown, A is straight and B is slightly curved. Equations for the curves are given in the text.

Fig. 2 Calculated third harmonic (8.55 GHz) radiation patterns produced by electron bunches from an S-band (2.85 GHz) Linac. The path lengths in air are 70, 90, and 150 cm. Vertical scale is arbitrary and the same for all three curves.

Fig. 3 Calculated third harmonic radiation patterns produced by electron bunches from an S-band Linac. The solid curve is for a path in air of 1000 cm, and the dotted curve is for a path length of 10,000 cm. Vertical scale is arbitrary and the same for both curves but much reduced from that of Fig. 2.

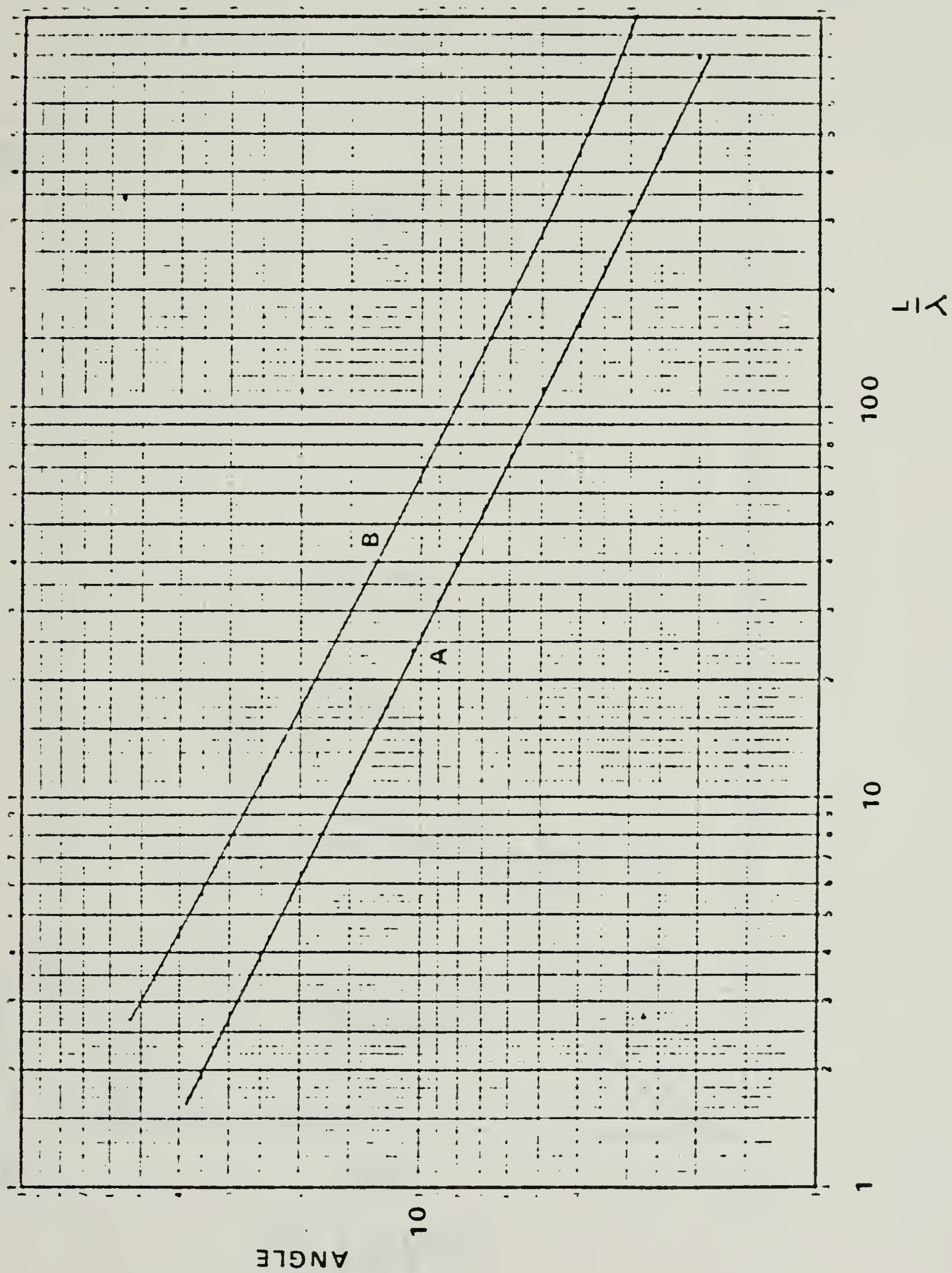

Figure 1

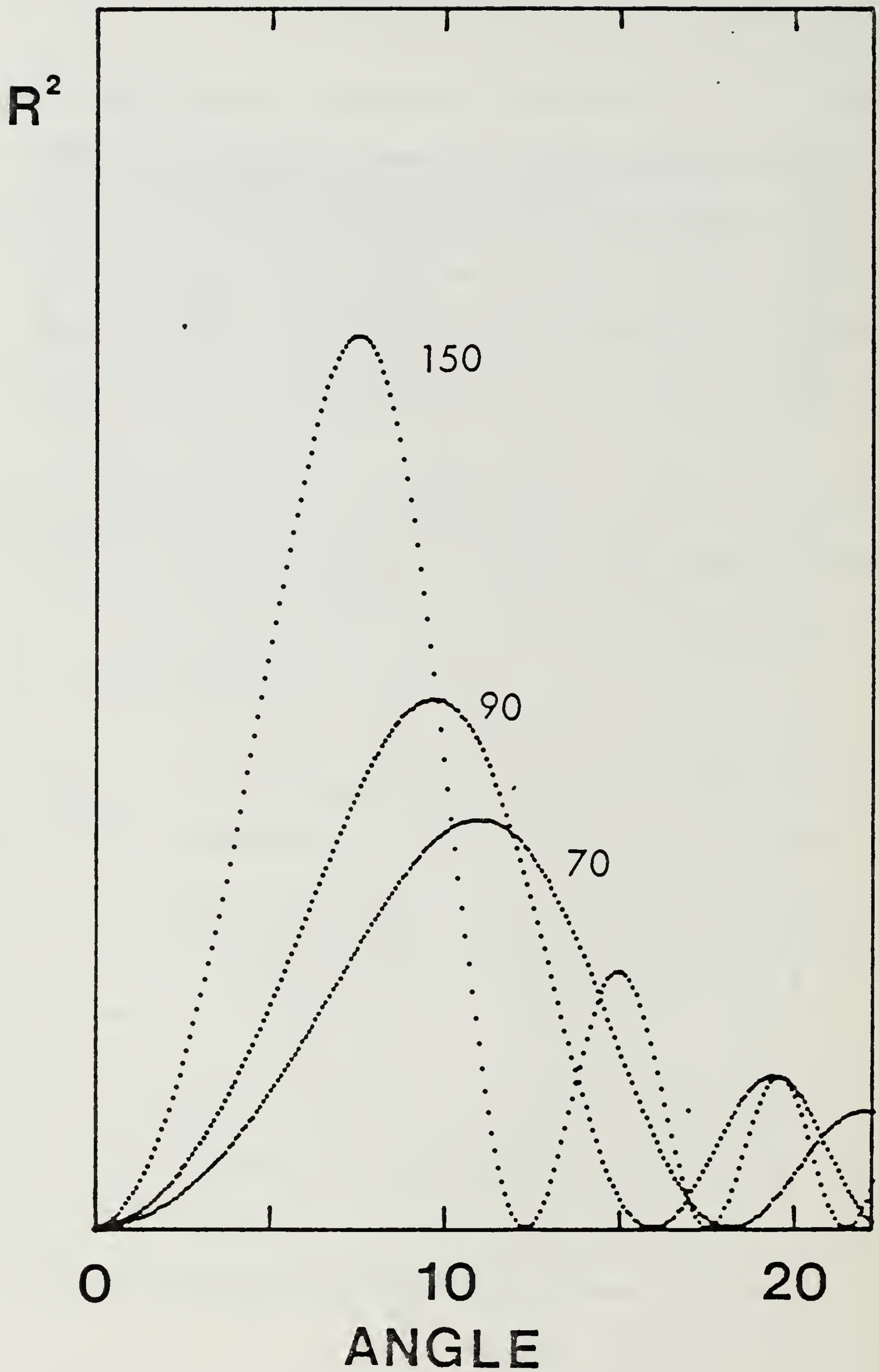

Figure 2

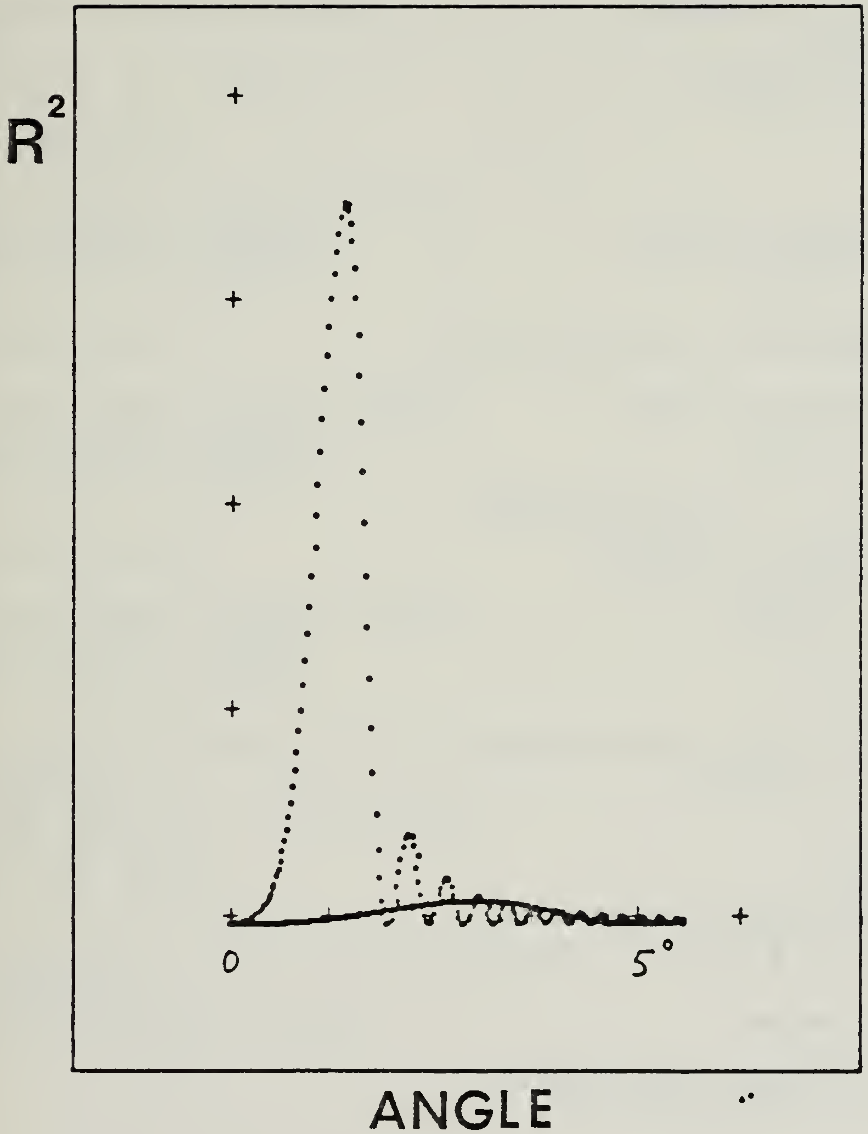

Figure 3

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